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Piezoelectricity for Transduction Applications

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Abstract
Piezoelectric effect is the ability of certain materials such as piezo-ceramics and piezo-polymers to generate an electric charge in response to applied mechanical stress. The process can also go in the reverse direction. This finds applications in the development of actuators, resonators, precision motors. This paper presents the study of the electrical output characteristic of electromechanical transducer for sensing application using Lead Zirconate Titanate (PZT-5H) as piezoelectric material. The results of the study showed that as the input mechanical forces range from 0 N to 8 N for applied linear mechanical force and from 0 N to sin(6πt) N for applied harmonic mechanical force, the corresponding electrical output voltages generated range from 0 V to 5.5x10^{-5} *V for linear input and 0 V to 45x10*$^{-5}$ *V for harmonic input. The amplification and measurement of the electrical response of the system as a direct proportion of the applied mechanical force is a suitable technique for the development of electromechanical transducer system.*

Keyword: *piezoelectric, transducer, actuator, electric charge, mechanical stress, dielectric*

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I. INTRODUCTION

A piezoelectric transducer employs the principle of piezoelectric effect to measure changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge [1].

Piezoelectricity is the phenomenon that describes the material property that is concerned with the transformation of electrical energy into mechanical deformation and vice versa. Put differently, it is the ability of certain materials such as piezo-ceramics and piezo-polymers to generate an electric charge in response to applied mechanical stress. The process can also go in the reverse direction. Thus, direct piezoelectric effect is the generation of electricity when mechanical stress is applied which is applicable in the development of transducers, accelerometers, energy harvesters. On the other hand, converse piezoelectric effect is the generation of stress or strain when an electric field is applied. This finds applications in the development of actuators, resonators, precision motors.

With the application of force on the material, movement of dipoles in the material to orient them in a particular direction occurs which in turn generates electric charges on the surface electrode of the material and this is referred to as poling [2]. This makes the application of piezoelectricity very useful in industrial processes. Application areas include, timekeeping using quartz resonance, microphones, radio antenna oscillators, speakers, hydrophones, and fuel injection. Other emerging technologies include energy harvesting and electronic sensing systems [3, 4]. By virtue of increasing global energy demand, research has been focused on developing technologies that can convert ambient environmental conditions such as mechanical vibration to useful energy or signal either as energy harvester or sensing system. Additionally, a plethora of composites and nanostructure materials have also been developed and can be fabricated as thin films, discs, or stacked sheets.

The aim of this work is to study the electrical output characteristic of piezoelectric transducer for sensing application. The objectives include:

- Definition of piezoelectric material properties for the design of the proposed sensing device;
- Simulation study of microelectromechanical system device;
- Analysis of the system's output characteristic.

II. LITERATURE REVIEW

Many research studies have shown that piezoelectric devices can be designed and deployed for sensing applications, as well as, for energy harvesting. Abidin et al [5] presented the design of piezoelectric array configuration for optimal production of electric energy for power systems application. It was also reported that the parameters that influence the output response of the device include, the type of piezoelectric material used, array configuration, ac-to-dc conversion process etc. For transduction or sensing application, Bazaei et al [6] proposed piezoelectric transducer integrated with high-speed nano-positioner for the measurement of displacement with wide frequency bandwidth and low noise. The sensing device provides accurate measurement of position as long as the nano-positioner displacement is within the sensing bandwidth. Mahadeva et al [7] developed and fabricated a paper-based piezoelectric sensing device. Barium titanate nanostructures embedded on wood fibers were used in the fabrication process and carboxyl cellulose, a paper strength-enhancing additive was employed in the process to improve the bonding of the piezoelectric material.

A study was carried out by Wang et al [8] on a hybrid sensing device based on multi-piezoelectric effect. This integrates the structure and function of sensor with actuator on a single piezoelectric element. The simulated system was analyzed using 3-D finite element model and the results obtained showed that the combined functions of sensor and actuator could be achieved on single piezoelectric crystal. Johari and Rashid [9] presented the development of a disc-based piezoelectric transducer to efficiently convert mechanical vibrations into electrical energy. This was done by applying pressure onto the disk which in turn converted it into an electrical output. The system response voltage can be used to detect and measure mechanical stresses.

As presented by Nguyen and Curry [10] in their work on biodegradable piezoelectric sensor which focused on monitoring vital physiological pressures for clinical diagnosis. The proposed implantable pressure sensing device was designed to be flexible and biodegradable, to avoid invasive removal surgery that can damage directly-interfaced tissues. In the work of Kon and Horowitz [11], the design and fabrication of a high-performance piezoelectric strain sensor was presented. The sensing device used microelectromechanical systems technology with the objective of achieving a point sensor for monitoring vibrations in a system. The performance analysis was based on the characterization of its output response voltage. Piezoelectric-based sensing techniques for monitoring of structural health was presented by Jiao et al [12]. The proposed methods range from piezoelectric electromechanical impedance and ultrasonic wave methods to a class of cutting-edge self-powered sensing systems employing the principle of the piezoelectric effect to monitor structural health. Muralt et al [13] developed a piezoelectric microelectromechanical systems (MEMS) device to achieve high sensitivity microsensor. Thin films were used in the design of the device to measure displacement in terms of voltage response levels. The impact of composition, orientation, and microstructure on the piezoelectric properties of the thin film sensor was also investigated.

2.1 Theoretical Formulation

The working principle of piezoelectric transducer is based on the effect of the application of mechanical stress to a piezoelectric material which causes a deformation in the internal structure of the material and thus generates electric charges on the surface of the material in response to the applied mechanical stress [14]. The principle of piezoelectricity is used widely for passive and active monitoring of structural systems. Piezoelectric effect is a mutual coupling between electrical and mechanical variables in the material (mechanical stress, strain, and electrical field or charge) which can be described in equations (1) and (2) [6]:

$$S_{ij} = S^E{}_{ijkl}T_{kl} + d_{ijm}E_m \quad (1)$$

$$D_n = d_{nkl}T_{kl} + \mathcal{E}^T{}_{mn}E_m \quad (2)$$

Where S_{ij}, T_{kl}, D_n and E_m correspond to the mechanical strain, stress tensors, electric displacement, and field vectors, respectively. Although the constitutive equations of piezoelectricity are in tensor form, a piezoelectric device can often be described by scalar equations as shown in equation (3) and (4).

$$\delta = S^V F + dV \quad (3)$$

$$Q = dF + C^F V \quad (4)$$

Where:

δ: Deflection or displacement of the piezoelectric device;
Q: Charge on the terminals of the piezoelectric device;
F: Force exerted on the device;

V: Voltage across the electrodes;
S^V: Compliance under constant voltage;
d: Piezoelectric coefficient;
C^F: Capacitance under constant force.

In general, piezoelectricity implies the production of an electrical charge from a piezoelectric material when mechanical stress is applied [5]. The reverse mechanism is that, a mechanical stress is produced when an electrical charge is applied.

III. MATERIALS AND METHODS

The methodologies employed in this work is depicted by the workflow shown in Figure 3.1.

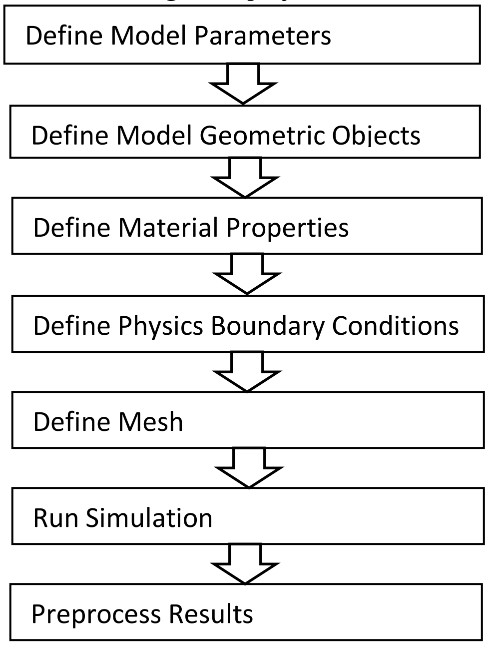


Figure 3.1: Workflow for Piezoelectric Transducer Simulation Study

COMSOL Multiphysics was used for a time-dependent study of the piezoelectric sensing device which was set up in a fixed-free mode. The setup was such that the system was fixed on one side and free on the other to receive harmonic perturbation. The modeling of the system was done in two-dimensional (2D) space, to create, analyze, and visualize the model's multi-physics, namely, solid mechanics, electrostatics and piezoelectric effects.

A. Definition of Model Parameters

Model parameters defined for the piezoelectric transducer include the geometric object dimension, as well as, the initial values of the electrodes' potentials and the applied forces. Harmonic and linear applied forces were defined in equations (5) and (6) respectively:

$$f_1 = A\sin(2\pi t) \quad (5)$$

$$f_2 = At \quad (6)$$

B. Definition of Model Geometries

The geometric objects that were defined for the proposed study include: top floating potential electrode and bottom ground electrode. Electrodes are used to collect charges or to apply electric field. The two-dimensional (2D) model layout of the piezoelectric transducer is as shown in the Figure 3.2. The object dimensions defined for the different geometries used in the simulation study are as shown in Table 3.1.

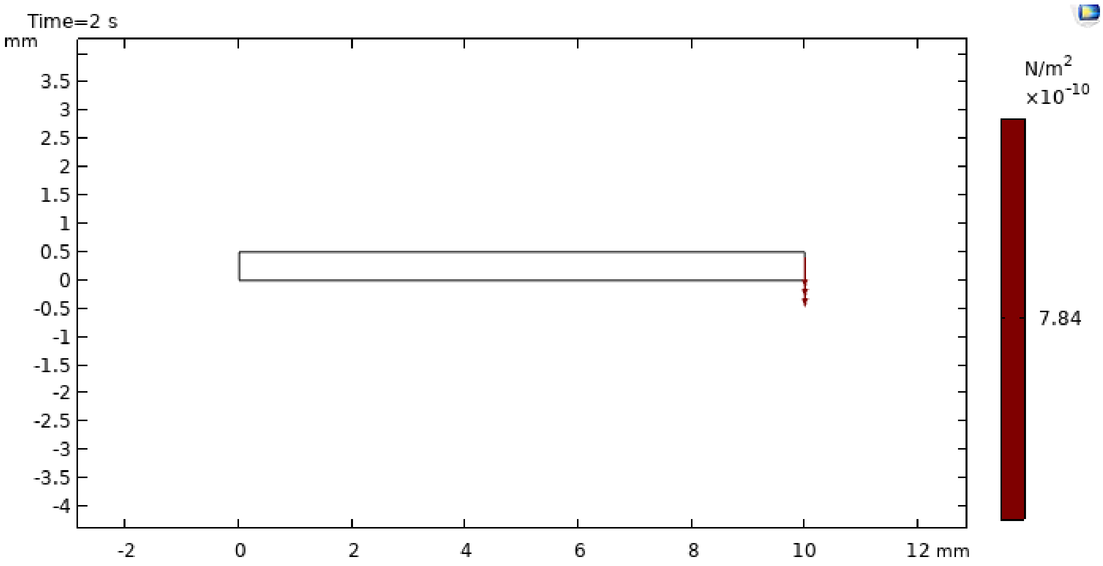


Figure 3.2: Model of Piezoelectric Transducer in Two-Dimensional Space

Table 3.1: Geometric object dimension for Piezoelectric transducer Model

Geometry	**Dimension (mm)**
Width	10
Height	0.5
Out-of-plane depth	5

C. Definition of Material Properties

The crucial material properties that define piezoelectricity include the coupling constant and relative permittivity. Lead Zirconate Titanate (5H) was used as piezoelectric material used for the transducer device. The properties of the material as follows [16]:

Table 3.2: Lead Zirconate Titanate (PZT-5H)

Property	Value
Crystal symmetry class	Uniaxial
Density	7500 kg/m^3

Detailed consitutive data in Strain-Charge format [16], namely, compliance, piezoelectric coupling, relative permitivity are as indicated in equations (7), (8) and (9):

$$Compliance, S_E = \begin{vmatrix} 16.5 & -4.78 & -8.45 & 0 & 0 & 0 \\ -4.78 & 16.5 & -8.45 & 0 & 0 & 0 \\ -8.45 & -8.45 & 20.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 43.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 43.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 42.6 \end{vmatrix} x10^{-12} \quad (7)$$

$$Piezoelectric\ Coupling, d = \begin{vmatrix} 0 & 0 & 0 & 0 & 741 & 0 \\ 0 & 0 & 0 & 741 & 0 & 0 \\ -274 & -274 & 593 & 0 & 0 & 0 \end{vmatrix} x10^{-12} C/N \quad (8)$$

$$Relative\ permitivity = \frac{\varepsilon_T}{\varepsilon_0} = \begin{vmatrix} 3130 & 0 & 0 \\ 0 & 3130 & 0 \\ 0 & 0 & 3400 \end{vmatrix}, \varepsilon_0 = 8.854\, x10^{-12} F/m \quad (9)$$

D. Definition of Physics Boundary conditions

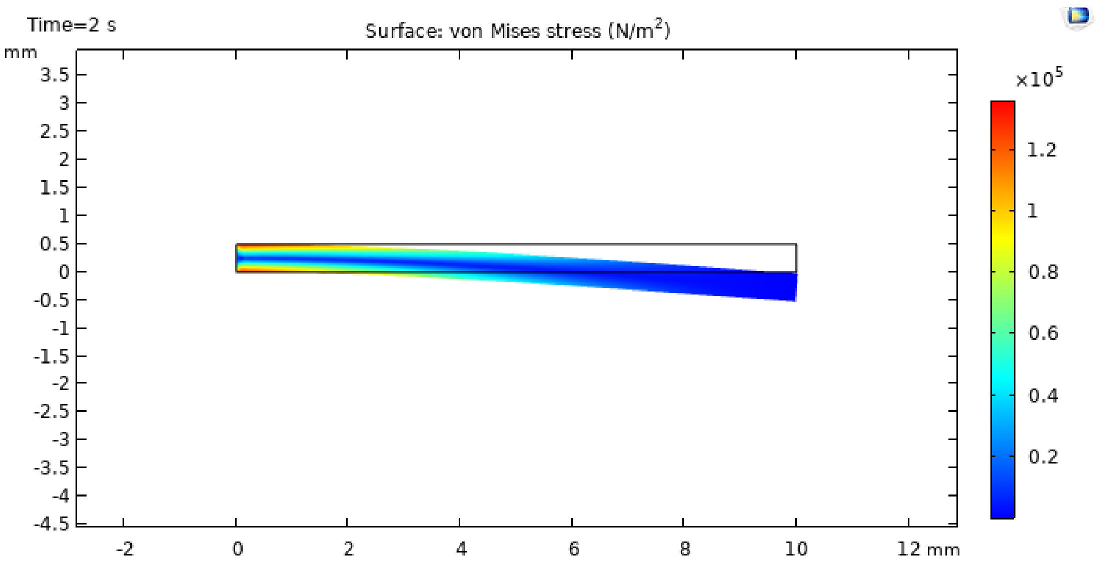
From the defined physics of electrostatics which governs the piezoelectric output characteristic of the proposed system, namely, voltage potential. The top potential electrode and bottom ground electrode were initialized as defined boundary conditions. From the physics of solid mechanics, the boundary conditions were such that the applied forces to the transducer model were sinusoidal input force sin(6πt) and ramp input force 4t, time, t ranges from 1 to 2 seconds.

E. Definition of Mesh

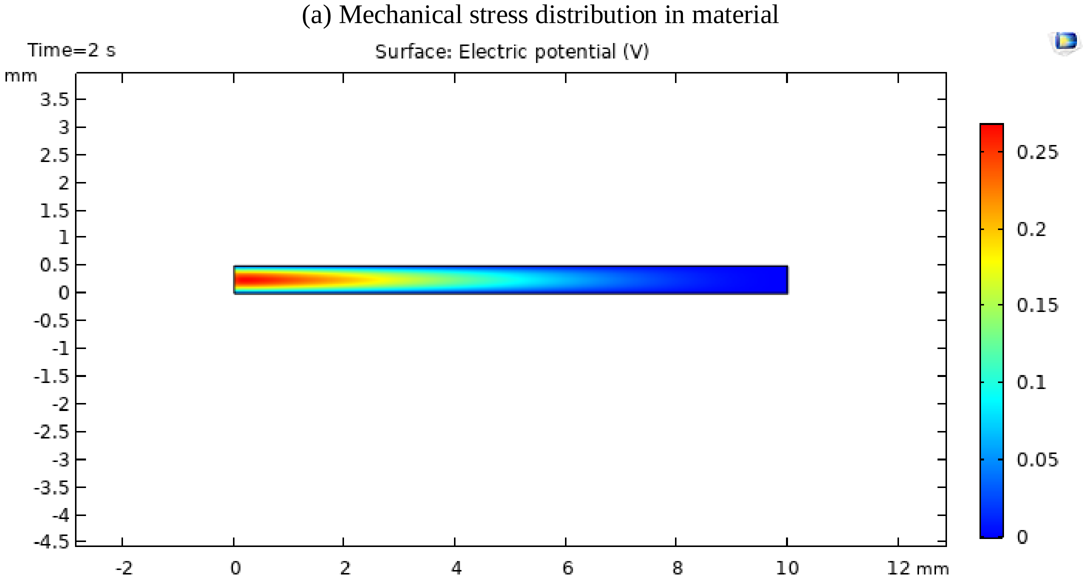
The mesh generator discretizes the domains into triangular mesh elements. The sides of the triangles are called mesh edges, and their corners are mesh vertices. Extremely fine triangular mesh was employed for the simulation study.

IV. RESULTS AND DISCUSSIONS

Time-dependent simulation was carried out to study the effect of the mechanical input to the system as well as the electrical response characteristic over a time range of 1 to 2 seconds. The diagrams of the simulation results are as shown Figure 4.1.



(a) Mechanical stress distribution in material



(b) Electric potential distribution in material

Figure 4.1: Simulation of mechanical stress and electric potential distribution in material.

A. Preprocessing of results

Preprocessing of results involved the generation of graphical plots of the electrical output characteristic of the simulated piezoelectric transducer. In this study, the effect of the applied harmonic and linear input forces on the transducer's electrical output responses was investigated. The system responses are directly proportional to the inputs. As shown in Figures 4.2 and 4.3, the application of harmonic mechanical input produced a corresponding harmonic electrical response. Additionally, in Figure 5, the application of a linear mechanical input produced a corresponding linear electrical response

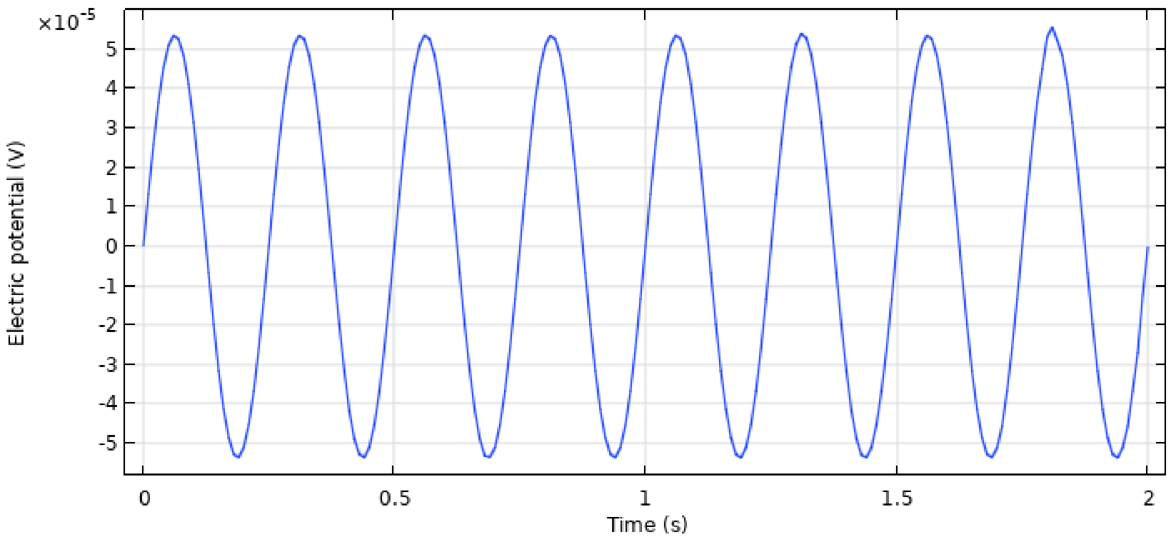


Figure 4.2: Plot of output electric voltage in response to harmonic mechanical input

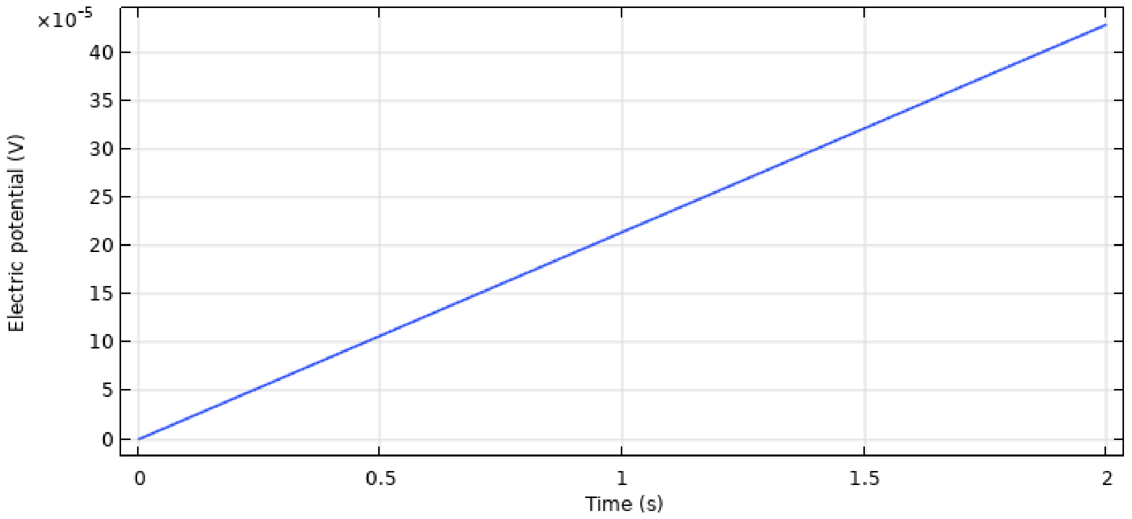


Figure 4.3: Plot of output electric voltage in response to linear mechanical input

From the results obtained, the applied input mechanical forces range from 0N to 8N for linear force and from 0N to sin(6πt) N for sinusoidal force, the corresponding electrical output voltages generated range 0V to $5.5x10^{-5}$ V for linear input and 0V to $45x10^{-5}$ V for sinusoidal input. The maximum output voltage magnitude of 45x10-5 V was generated in response to the input force of 8N while a maximum output voltage of 5.5x10-5 V was generated in response to the input harmonic mechanical force of sin(6πt). These results highlight the potentials of the proposed piezoelectric transducer based on LZT-5H for electromechanical sensing application.

V. CONCLUSION

This paper focused on the simulation study of the output response characteristics of a piezoelectric transducer based on Lead Zirconate Titanate (LZT-5H). The system design was modeled on the piezoelectricity concept of generating electrical output in response to an applied mechanical stress input. The study showed that as the input mechanical forces range from 0 N to 8 N for applied linear mechanical force and from 0 N to sin(6πt) N for applied harmonic mechanical force, the corresponding electrical output voltages generated range from 0 V to 5.5×10^{-5} V for linear input and 0 V to 45×10^{-5} V for harmonic input. The amplification and measurement of the electrical response of the system as a direct proportion of the applied mechanical force is a suitable technique for the development of electromechanical transducer system.

Declaration of Interest

The author declares no conflict of interest

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